A New 70-Meter Antenna Quadripod With Reduced RF Blockage

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The new subreflector mount (quadripod) for the 64-meter to 70-meter antenna extension project was the result of many trial designs aimed at reducing RF spherical and plane wave blockage and minimizing structural weight while satisfying strength and natural frequency requirements. An optimum design emerged which has a gain improvement of 0.32 dB over the present 64-meter design. This article describes some of the trial designs made and the final optimum configuration selected.

I. Introduction

The 64-Meter Antenna Rehabilitation and Performance Upgrade Project at the Jet Propulsion Laboratory (JPL) initially aimed at increasing the gain by about 1.9 dB at X-band (8.45 GHz) for the upcoming Voyager-Neptune and Galileo-Jupiter encounters. The effort entails the following:

(1) Increasing the antenna aperture from 64 to 70 meters (+0.8 dB).

(2) Resurfacing the entire primary reflector with high quality panels and aligning those panels with high precision optical theodolites and holographic methods (+0.5 dB).

(3) Shaping the subreflector to an asymmetric surface and the main reflector to an axisymmetric surface in order to obtain a uniform RF radiation pattern (+0.3 dB).

(4) Automating the axial (z-axis) and y-axis focusing controllers of the subreflector positioner and adding structural stiffening braces to the main reflector central truss to reduce gain loss induced by gravity loads when the antenna is tilted at extreme elevation angles (+0.3 dB).

(5) Employing any modifications that may add to the total 1.9 dB gain increase and add a level of confidence to the upgrade project.

Since the subreflector mount was to be redesigned anyway, a vigorous effort, funded jointly by the Advanced Systems Technology and the TDA Engineering offices at JPL, was undertaken to investigate different quadripod configurations that showed a promise in reducing the RF blockage. When compared to the other structural and mechanical modifications, the quadripod yielded the greatest potential gain improvement for its cost. A thorough review of candidate designs was made, and several were selected to be studied.

II. Design Requirements

For each new configuration, the following requirements were in effect:

(1) The total RF blockage (planar and spherical wave) due to the quadripod legs should be no greater than the percentage aperture area blockage for the current 64-meter antenna. If possible, the blockage should be minimized.

(2) The natural frequency of the lowest mode of the quadripod should be equal to or greater than that for the present 64-meter antenna quadripod to be compatible with the existing servo system.

(3) The lateral (y-gravity) displacement of the subreflector should not be excessive due to the limited capability of the subreflector positioner to correct for it (9 in. range).

(4) The quadripod should conform to the structural strength criteria set forth in the ASCE Tower Code (Ref. 1) under varying gravity loading, corresponding to different antenna elevation angles. Furthermore, the quadripod should accommodate a larger, heavier subreflector and subreflector positioner and be able to withstand safely the lifting loads of the feedcone and subreflector hoists.

(5) The quadripod should be an "optimum" design rather than just a "working" design, i.e., it should satisfy the above performance constraints with minimum truss weight. Material cost savings are related to weight reduction.

III. Definition of Blockage

The beam of transmitted or received energy includes all rays parallel to the axis of the paraboloid that fall within the aperture of the paraboloid. The beam intensity is assumed to be uniform over its circular cross-section. The blockage area is defined as that portion of the beam cross-section representing the optically obstructed rays (Ref. 2). It can be considered as the sum of two kinds of blockage: (1) the blockage that occurs where the wavefront is spherical, and (2) the blockage that occurs where the wavefront is plane. Spherical wave blockage is the shadow of the quadripod legs projected on the paraboloid when they are illuminated from the focus. In Fig. 1, this is the shaded area outside the dashed circle. Plane wave blockage is the projection of the subreflector and quadripod onto a plane and corresponds to the shaded area inside the dashed circle.

Without an explicit function to relate optical blockage to the RF antenna efficiency, the following empirical equation valid for small B was used to relate the percent of blocked area to aperture area, B, and aperture efficiency, η,:

$$\eta = [1 - 1.2(B/100)]^2$$

For the purpose of this study, the quadripod legs were assumed 100% opaque. Since the inner face of the legs would be constructed from steel plates to simplify fabrication, this assumption is not only conservative but accurate. Also, gain loss due to the subreflector plane wave blockage is not included in the gain loss values given in Tables 1 and 2, because its effect is usually accounted for in the microwave efficiency estimate. The "net blockage," as defined here, includes optical plane wave and spherical wave blockage by the quadripod legs only.

IV. Methodology

Three different options to reduce RF blockage by the quadripod are indicated in Fig. 2. In order of increasing reduction potential, they are: (1) increase $R1$ by attaching the legs to the main reflector surface at a point farther from the paraboloidal axis; (2) increase the pitch angle β to make the legs closer to the vertical; and (3) change the cross-section of the legs by reducing the widths of the inner and outer faces, Wi and Wo. The first option would have required extensive modification of the existing main reflector rectangular girder structure to attach the quadripod. Excessive fabrication and erection costs caused this option to be eliminated. The second option reduces spherical wave blockage by moving the inner face of the legs farther from the primary focus of the Cassegrainian system. It also increases the size of the apex, Wa, but this had to be done anyway to accommodate the larger subreflector. The magnitude of the pitch angle was restricted, however, to that necessary for reasonable clearance of the subreflector. The third option became the key to the study and proved to be quite effective.

Using the JPL-IDEAS structural optimization computer program to perform analysis and design, a series of pin-jointed truss finite element models of candidate designs was generated. The performance of the various quadripod geometries was determined for each of the required loading conditions. In each case the member connectivity (or topology) was maintained while the dimensions or proportions of the quadripod leg cross-sectional width profile (Fig. 2, Sec. A-A) were changed. The widths of the parallel faces were selected so that they were "balanced," that is,the outer face (Wo) lay within the spherical wave shadow generated by rays impinging on the inner face (Wi). Minor changes in apex dimensions were made as necessary to match the width changes. The selection of a trapezoidal cross-section minimizes blockage while maximizing quadripod leg torsional stiffness, which is a function of the enclosed cross-sectional area. Also, due to the symmetry of the structure, it was possible to use only half models; this reduced computer computation costs.

V. Trial Designs

Table 1 compares the 64-meter antenna quadripod finite element model with the four best 70-meter trial configurations. All were pin-jointed truss models. For each trial design case, the objective was to meet or exceed the first mode (torsional) frequency of the 64-meter quadripod model while minimizing the structure weight. The gravity displacement of the subreflector was monitored but was not usually imposed as a design constraint.

As the cross-section of the leg was reduced, so was the net blockage. As shown in the table, this reduction is accompanied by a decrease in natural frequency and an increase in gravity displacement of the subreflector. The progressive drop in weight in Models 1, 2, and 3 resulted from a reduction in length of certain leg truss members as well as the relative ease with which the structure met the design constraint.

Model 4 represents a different situation. The increase in structure weight indicated a difficulty in meeting the constraint with a very slender quadripod leg profile. Nevertheless, the weight increase was within acceptable limits, and Model 4 did meet the design constraint; it was selected as the final configuration because of its low blockage.

The "acceptable weight" limitation was not so much a requirement as a guideline. Since these were stand-alone quadripod models, it was not possible to determine directly their effect on the reflector back up truss structure without costly analyses of the larger tipping structure model. Also, the quadripod would be counterweighted, and available space for counterweight was limited. Nevertheless, subsequent analysis of the composite back up structure with quadripod computer models showed no significant penalties resulting from this design.

VI. Final Design

Trusses are usually analyzed as pin-jointed structures. In reality they are not pin-jointed because of bending and torsional stiffness at the rigid corners, but axial forces in the truss members predominate so bending and torsional moments are often neglected. An analysis of a rigid-joint 64-meter quadripod model, however, showed a substantial increase in torsional natural frequency (from 0.74 Hz to 1.22 Hz), whereas a rigid-joint 70-meter model did not (from 0.78 Hz to 0.82 Hz). To achieve the higher 64-meter frequency, the final configuration had to be redesigned.

Primarily a computer program redesign sequence consists of resizing truss members without altering the overall proportions or dimensions of the model. Unfortunately, the topology of Model 4 made it unreasonable to attempt to meet this higher natural frequency constraint by only resizing members; the optimization algorithm in IDEAS, in achieving its best solution, reached a point where the effect of additional structural stiffness was offset by the associated increase in structural mass. At this point, the natural frequency had been maximized and could only be increased by reducing nonstructural weight, which was invariant.

Because of an unwillingness to abandon this configuration (because of its blockage reduction potential), a new modification was proposed: outrigger braces, as sketched in Fig. 3, were added to connect the lower portion of the quadripod legs with additional points on the reflector back up truss. These braces resist the rotation of the legs about their longitudinal axis (which was evident from an examination of the first mode shape) and thereby increase the frequency. The results are listed in Table 2. Compare the results to Model 4 in Table 1, and note the reduced quadripod structural weight as an additional benefit. An insignificant increase in net blockage is due to the outriggers.

VII. Supplementary Results

Additional observations, resulting from other analyses performed during the course of the study, are briefly discussed below:

(1) For a given quadripod geometry, increasing the aperture area while keeping other parameters constant causes an increase in spherical blockage area, and the percentage increase in spherical blockage is much greater than the percentage increase in aperture area.

(2) Varying the leg depth had no appreciable effect on either blockage or the frequency of the first mode.

(3) The first mode shape indicated a rotation of the nearly rigid apex about the focal axis; the legs showed weak-axis bending. An attempt to reduce this bending by using K-braces to subdivide the bays of the outer face produced improved but limited results due to the extreme slenderness of the quadripod legs.

(4) Efforts to meet the torsional frequency requirement included supplementing the apex structure by adding members across the axis of symmetry. This was done early in the study, and results indicated that the connectivity of the apex could be simplified without affecting the first mode frequency. These supplementary members were then removed.

(5) The second mode of the stand-alone quadripod model exhibited sideways bending at a frequency 0.5 Hz

higher than the first mode. Modes higher than two had frequencies in excess of twice the first mode frequency.

(6) For the composite back up structure with quadripod model, the lowest mode was quadripod torsion at a frequency slightly less than the first mode of the stand-alone quadripod model.

VIII. Conclusions

The following are conclusions from the quadripod blockage reduction analysis:

(1) Varying the inner and outer face widths had a significant effect on the quadripod blockage and fundamental frequency.

(2) The torsional frequency performance constraint controlled the design. In all cases, the requirement on the y-gravity displacement of the subreflector was easily satisfied.

(3) Experience with the 64-meter quadripod model indicates that a pin-jointed model yields a torsional natural frequency much lower than measured on the actual structure. A rigid-jointed model, which accounts for bending and torsional stiffness of the truss members, gives more realistic results. The 70-meter quadripod model performance was insensitive to the joint continuity. Again, this is probably attributable to the leg slenderness.

(4) The quadripod legs are usually pin-connected to the reflector truss back up structure. This type of connection cannot resist bending or twisting moments and therefore allows the legs to rotate about their longitudinal axis, which is evident from the mode shape. Limiting this rotation greatly increased the first mode frequency; it required the addition of outrigger braces near the base of the quadripod legs to provide torsional rigidity.

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Table 1. Trial designs to reduce RF blockage. All models are pin-jointed.

Parameter	64-m Antenna	70-m Antenna Model 1	70-m Antenna Model 2	70-m Antenna Model 3	70-m Antenna Model 4
Wi, in. (m)	18.0 (0.457)	18.0 (0.457)	18.0 (0.457)	15.0 (0.381)	11.0 (0.279)
Wo, in. (m)	36.0 (0.914)	36.0 (0.914)	32.0 (0.813)	28.0 (0.711)	20.0 (0.508)
H, in. (m)	96.0 (2.438)	96.0 (2.438)	96.0 (2.438)	96.0 (2.438)	96.0 (2.438)
Net Blockage, %	6.34	5.67	5.01	4.44	3.32
Loss, −dB	0.68	0.61	0.54	0.48	0.35
Structure Weight, lb (kg)	41,600 (18,869)	54,258 (24,611)	54,174 (24,573)	53,174 (24,119)	59,146 (26,828)
Gravity Displacement of Subreflector, in. (m)	0.89 (0.0226)	1.25 (0.0318)	1.26 (0.0320)	1.30 (0.0330)	1.48 (0.0376)
Lowest Torsional Frequency, Hz	0.74	1.23	1.13	0.99	0.78

Table 2. Comparison of current 64-m quadripod with final 70-m design. Both models are rigid-jointed.

Parameter	64-m Antenna	70-m Antenna
Wi, in. (m)	18.0 (0.457)	11.0 0.279)
Wo, in. (m)	36.0 (0.914)	20.0 (0.508)
H, in. (m)	96.0 (2.438)	96.0 (2.438)
Net Blockage, %	6.34	3.42
Loss, – dB	0.68	0.36
Structure Weight, lb (kg)	41,600 (18,869)	53,250 (24,154)
S/R and Positioner Weight, lb (kg)	12,400 (5,625)	24,000 (10,886)
Gravity Displacement of Subreflector, in. (m)	0.89 (0.0226)	1.16 (0.0295)
Lowest Torsional Frequency, Hz	1.22	1.42
Lowest Pitch Frequency, Hz	1.42	2.65

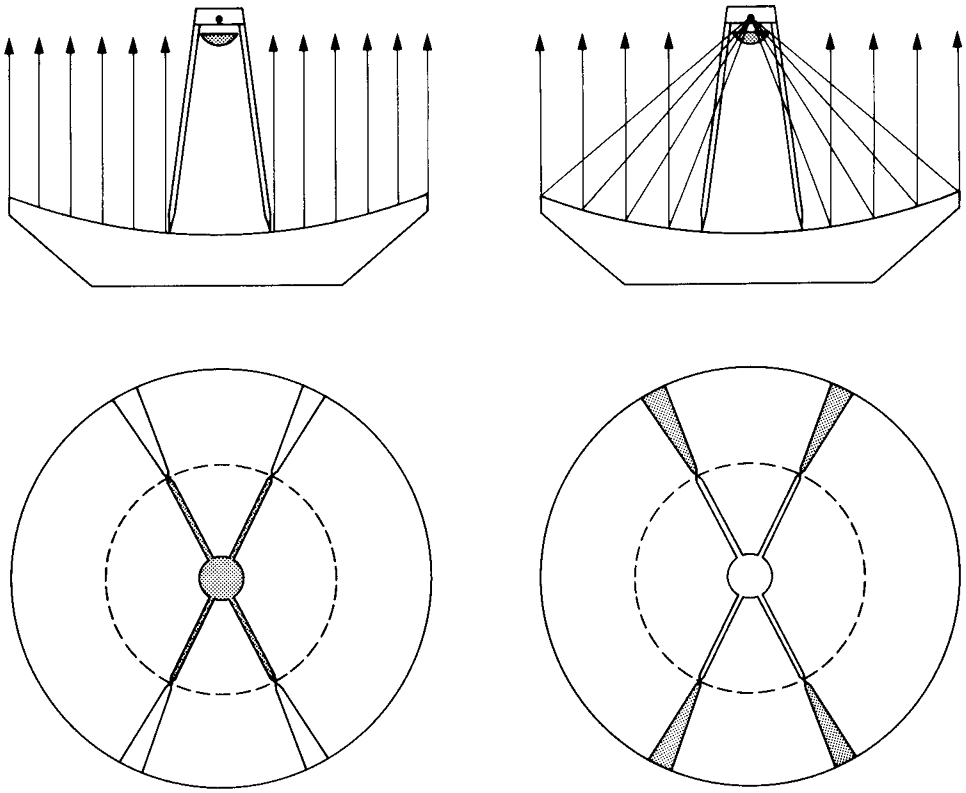

Fig. 1. Plane wave and spherical wave blockage

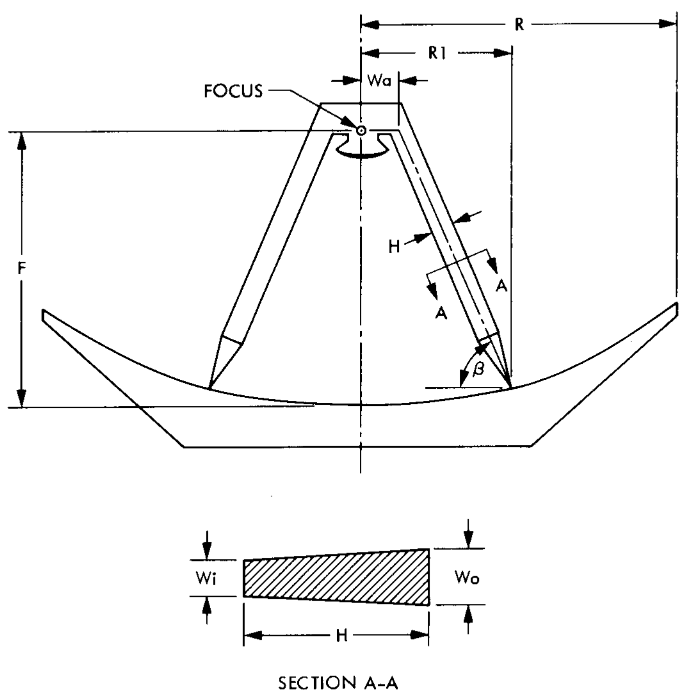

Fig. 2. Parameters controlling RF blockage

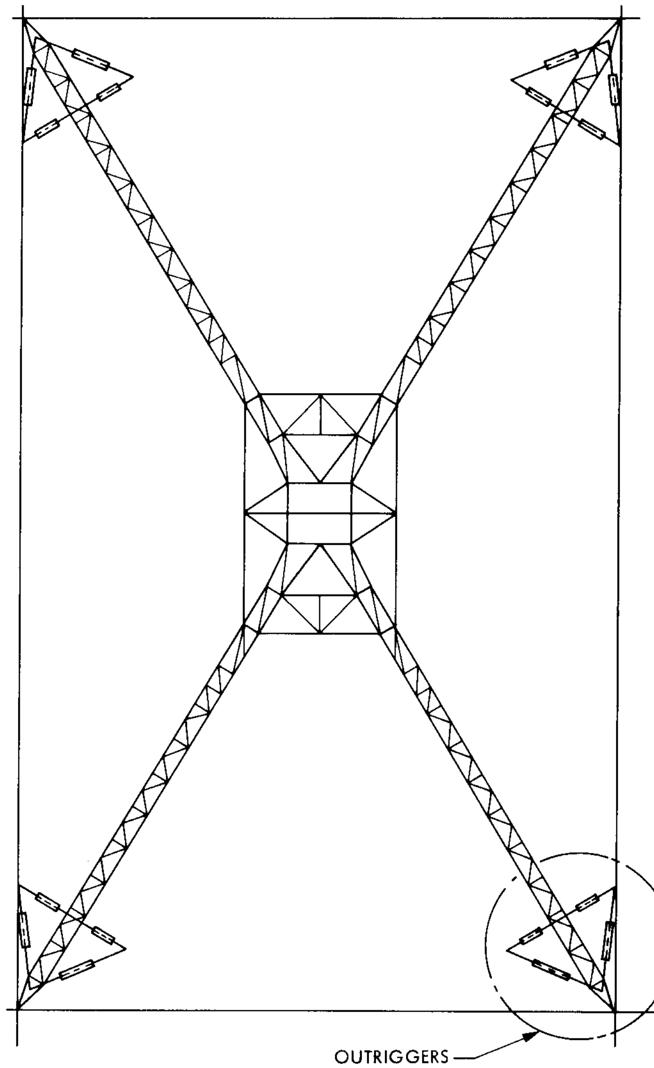

Fig. 3. Plan view of 70-meter quadripod with outriggers